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FINAL TECHNICAL REPORT

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Field Testing of Thermal Canopy Models in a Spruce-Fir Forest

1. INTRODUCTION

Recent advances in remote sensing technology allow the utilization of the thermal infrared region to gain information about vegetative surfaces. Extending existing models to account for thermal radiance transfers within rough forest canopies is of paramount importance. This is so since all processes of interest in the physical climate system and biogeochemical cycles are thermally mediated. Model validation experiments were conducted at a well established boreal forest/ northern hardwood forest ecotone research site located in central Maine. Data was collected to allow spatial and temporal validation of thermal models. Emphasis was placed primarily upon enhancing submodels of stomatal behavior, and secondarily upon enhancing boundary layer resistance submodels and accounting for thermal storage in soil and vegetation.

In recent years, intensive research has been conducted in the ecophysiological processes of coniferous forests in temperate regions such as northwestern North America and northern Europe. Several species including Sitka spruce (*Picea sitchensis*), Scots pine (*Pinus sylvestris*), and Douglas fir (*Pseudotsuga menziesii*) have been of particular interest because of their dominance, their significance in ecosystem interactions, and their economic importance. However, work on conifers has been limited because of the difficulties these ecosystems present for comprehensive studies of fundamental processes (Jarvis et. al., 1976). This is in part due to the fact that physiological parameters such as leaf area, water potential, and stomatal conductance are extremely difficult to measure because of the large size of these species. Moreover, it has also been difficult to find a sufficiently large, flat site within these ecosystems required for micrometeorological observations. Although some data have been collected on photosynthesis and plant-water relations in conifers (Jarvis & Morison, 1981; and Lassoie, 1982), more information is needed about the factors affecting stomatal behavior (transpiration) in these ecosystems.

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2. METHODS AND MATERIALS

2.1 Site Description

Experiments were conducted during the summer months of 1989 and 1990 near the town of Howland in eastern central Maine. The experimental site, located 45°10'N 68°40'W, is within the 6500 ha Northern Experimental Forest owned by International Paper. The topography of the region is mainly flat with slopes no greater than 4% in a 3 km radius from the data collection site. The climate in the region can be described as cold and humid with major weather events from the northwest and southwest directed by the continental jet stream. Summer weather in the region is characterized by cool temperatures seldom exceeding 30°C with moderate humidity throughout the season. Temperatures frequently as low as -20°C are characteristic of central Maine winters with continuous snowpack from December through March usually accumulating to 2m.

The Northern Experimental Forest lies within the ecotone between the boreal conifer forest to the north and the northern hardwood forest to the south. It is composed mainly of spruce and fir (*Picea rubens* and *Abies balsamea*, respectively) with a large component of eastern hemlock (*Tsuga canadensis*); and a less frequent component that includes eastern white pine (*Pinus strobus*), northern white cedar (*Thuja occidentalis*), and paper birch (*Betula papyrifera*).

The soils in the region, mostly developed from till, are predominantly acid, low in fertility and high in organic matter. Within the research forest and adjacent to the measurement site , podzolic soils have been identified as Aquic Haplorthods from the moderately-well drained Skerry series, and Aeric Haplaquods from the poorly drained Westbury series.

2.2 Measurements

Climatological, physiological and energy budget data were collected during 17 selected days during the summer months of 1989 and 1990 under primarily clear sky conditions. The forest around the site is relatively uniform in height with a mean of about 19.5 m and living biomass density of about 43 kg/m^2 . The surface is predominantly so covered for over 1 km in all directions providing good fetch for measurements taken from a 25.5 m walk-up platform tower. Measurements of windspeed were obtained with a Gill UVW anemometer (R. M. Young Co.) mounted on the tower 28 m above the forest floor. Net radiation was measured with a net radiometer (Rebs, Inc.). Sensible and latent

heat-flux measurements were obtained by eddy correlation using a one-dimensional CAL7 sonic anemometer with a fine-wire thermocouple (Campbell Scientific, Inc.) and a KH_2O krypton hygrometer (Campbell Scientific, Inc.). The data acquisition system for eddy correlation consisted of a Tecmar 16-bit analog to digital converter board and a IBM PC AT which were used to convert and process the raw data from the eddy correlation instruments, calculate the 1/2 hour averages, and store results. A basic-language program with a 10Hz scan rate for eddy correlation calculations was used in real time with printed outputs at the end of the averaging period (McMillen, 1986).

Ancillary measurements included profiles of air temperature and vapor pressure obtained at four levels (8.5, 13.5, 19.5 and 26.5 m), down-welling shortwave radiation and PAR (LiCor), soil heat flux by means of two heat flux plates (Thornthwaite Associates) at a depth of 0.08 m, soil temperature using thermocouples, and and profiles of soil water potential using moisture blocks. A CR7x and a CR21x datalogger (Campbell Scientific, Inc.) were used for acquiring these data.

In addition, measurements of canopy temperature were taken every half hour at the first three levels by using an infrared thermometer (Everest Interscience, Inc.). Physiological measurements made every hour included needle water potential and stomatal resistance. A pressure chamber was used to measure water potential; stomatal resistance was measured with a steady-state type diffusion porometer (LiCor).

3. THEORY

Measured evapotranspiration was utilized to estimate canopy resistance which in turn was used for determining the efficacy of modeled canopy resistance. Modeled resistance, calculated hourly, will be used in the thermal model to replace the estimated constant value previously used.

Monteith (1965) modified the Penman method of estimating evapotranspiration by introducing a surface (or bulk stomatal) resistance which accounts for physiological effects of the canopy on transpiration. The Penman-Monteith combination method is given by the following relationship:

$$ET=[\Delta(R_n-S)+\rho_a c_p(VPD)/r_a]/[\Delta+\gamma(1+r_c/r_a)] \qquad [1]$$

where Δ is the slope of the saturated vapor pressure temperature curve, Rn is net radiation, S is soil heat flux density and change in within canopy storage, ρ_a is air density, c_p is specific heat of air at constant pressure, VPD is the water vapor pressure deficit, r_a is the aerodynamic resistance, γ is the psychrometric constant, and r_c is the canopy (surface) resistance.

Of the terms in equation [1], S is the only one that has no direct means of measurement, except for soil heat flux. Thus S has to be evaluated analytically which may result in error because of the difficulty in measuring the temporal and spatial variability of temperature of the biomass and the temperature and humidity of the air within the canopy (Verma et. al., 1986). The heat flux (Wm^{-2}) stored in the soil-canopy system is given by

$$S = S_A + S_W + S_V + S_G \qquad [1.1]$$

where, the sensible heat flux stored in the canopy air is:

$$S_A = \int_0^{Zr} \rho_a c_p (\partial T_a/\partial t)\, \partial z \approx \rho_{avg} c_p \sum_{l=1}^{4} (\Delta T_{a_l}/\Delta t)\, \Delta z_l; \qquad [1.2]$$

the latent heat flux stored in the canopy air is:

$$S_W = \int_0^{Zr} (\rho_a c_p /g)(\partial e_a/\partial t)\, \partial z \approx (\rho_{avg} c_p /g_{avg}) \sum_{l=1}^{4} (\Delta e_{a_l}/\Delta t)\, \Delta z_l; \qquad [1.3]$$

the biomass heat storage is:

$$S_V = \int_0^{h} (\rho c)_{veg}(\partial T_{veg}/\partial t)\, \partial z \approx (\rho c)_{veg} \sum_{ll=1}^{3} (\Delta T_{veg_{ll}}/\Delta t)\, \Delta z_{ll}; \qquad [1.4]$$

and the soil heat flux storage is:

$$S_G = S_G(d) + \int_0^{d} \rho_s c_s (\partial T_s/\partial t)\, \partial z \approx S_G(d) + 103 \Delta T_{s_{avg}} \qquad [1.5]$$

where z is height, h is the mean canopy height, z_r is the height of net radiation measurement, and d is depth; l is the level of air temperature and humidity measurements, and ll is the level of canopy temperature measurements; subscripts 'a' denotes air, 'veg' vegetation, and 's' soil; average values are calculated from the ground up to the highest level in the canopy. A modified version of this storage analysis will be incorporated into the next version of the thermal model.

The use of equation [1] requires measurements of solar radiation, wind speed, air temperature, vapor pressure, soil heat flux and canopy heat storage as well as estimates of canopy resistance. However, several studies indicate that for rough canopies (i.e. conifer forests) equation [1] can be further simplified (McNaughton & Black, 1973; Jarvis, 1981; and Whitehead & Jarvis, 1981), since tall, rough canopies create aerodynamic resistance values one or more orders of magnitude smaller than the surface resistance. Consequently,

equation [1] can be simplified to the following:

$$ET_{imp} = [\,\rho_a\, c_p(VPD)/r_c]\,/\,\gamma \qquad [2]$$

The latent heat flux given by equation [2] is often called the "imposed transpiration rate", ET_{imp}, (Jarvis, 1985, Jarvis & McNaughton, 1986) and the canopy is said to be strongly coupled to the surrounding air.

The role of the aerodynamic resistance can become significant in smooth short vegetation which, by virtue of having less efficient aerodynamic transfer, is considered to be weakly coupled to the atmosphere. It is usually equal to or larger than the surface resistance since less rough vegetation results in less turbulence near the ground. Hence, evaporation from the surface proceeds at a rate dictated by the available energy. In such a case, the available-energy term in equation [1] is more significant than the vapor pressure-deficit term so that [1] can be further simplified to an equilibrium ET equation:

$$ET_{eq} = \Delta(R_n - S)/(\Delta + \gamma) \qquad [3]$$

The Penman-Monteith equation [1] can thus be described in terms of the imposed and equilibrium ET rates in the following form (McNaughton & Jarvis, 1983; Jarvis, 1985; Jarvis & McNaughton, 1986):

$$ET_c = \Omega_c ET_{eq} + (1 - \Omega_c) ET_{imp} \qquad [4]$$

where Ω_c is a dimensionless factor which is a measure of coupling or decoupling conditions between the canopy surface and the atmosphere and is given by:

$$\Omega_c = [(\Delta/\gamma) + 1]/[(\Delta/\gamma) + 1 + r_c/r_a] \qquad [5]$$

Omega (or decoupling coefficient) describes the extent to which transpiration from the canopy is made up by the equilibrium and imposed components, and ranges between 0 and 1. At the lower limit of $\Omega_c \approx 0$ strong coupling conditions exist and the vapor flux from the canopy is given by ET_{imp}. Conversely, when $\Omega_c \approx 1$ the canopy surface is decoupled from the surrounding air and the total transpiration rate is dominated by ET_{eq}.

For the forest, if either equation [1] or [2] is used, values for r_c must be obtained. We have chosen to use a model of Jarvis (1976) wherein the inverse of leaf stomatal resistance (conductance) is expressed as:

$$g = g^* f(PAR)\, f(T)\, f(VPD)\, f(\psi) \qquad [6]$$

where g is conductance, g* the maximum conductance, and f(PAR), f(T), f(VPD), and $f(\psi)$ are functions of PAR, leaf temperature, vapor pressure deficit, and leaf water potential, respectively, which vary from 0 to 1. Methodology for evaluating these functions and determining r_c are found in Baldocchi et al. (1987).

4. RESULTS

4.1 Energy Balance

Figure 1 shows typical energy balance data for daytime periods for two days. Bowen ratio values of from 1 to 1.4 midday prevailed for these and other days of measurement. Note the significant values of the storage term (S). Energy balance closure analysis for 328 half hour periods indicates closure errors of no more than 20% for 95% of the data.

4.2 Resistances and Ω_c

Day time conditions rarely departed significantly from neutral and calculated values of r_a were not stability corrected. Values of r_c were calculated from equation [1] using eddy correlation measurements of vapor flux. Figure 2 shows values of r_a and r_c for the same days as in Fig. 1. These data and those for all other days indicate that rc varied from 10 to 30 times that of r_a. Using equation [5] to evaluate the decoupling coefficents for all day time data indicates that Ω_c ranged from 0.03 to 0.35 with 95% of the data falling below 0.20. Therefore, equation [2] should yield useful estimates of vapor flux if values of r_c can be determined. This approach will also be tested in future versions of the thermal model.

4.3 Modelled ET

We used equation [6] to evaluate r_c following the radiation transfer model of Norman (1979) to determine f(PAR). From our porometer and environmental data we evaluted f(T) using Tmin = 0°C, Tmax = 38°C, and Topt = 12°C. The slope of our VPD function was -0.022 mb^{-1} and our maximum conductance was found to be 0.033 m/s. Since our leaf water potential never was less than -1.7 kPa and the threshold value for spruce is reported to be -2.1, we set $f(\psi) = 1$. Figure 3 demonstrates modelled and measured ET for the two days previously shown.

4.4 Revised Thermal Model

All model runs utilized measured Howland, Maine meteorological matrices, the canopy matrix file "dougfir", shortwave absorption coefficients of 0.5, 0.3, 0.1, ,and 24 simulation periods. The original model (MK1) with a constant stomatal resistance both day and night of 0.01 was run for several days. A revised model (MK2) allowing transpiration only during daylight hours was then run for the same days. A further revision of the model (MK3) allowed for variable stomatal resistance input by hours, as determined above.

Figures 4 and 5 show hourly differences between level 1 modelled and measured canopy temperatures for JD 214 comparing the MK1 and MK2, and the MK1 and MK3 model values, respectively. It is evident that use of variable stomatal resistance significantly improves model output. However, examination of Figures 6, 7, and 8 which delineate hourly variability of measured and modelled canopy temperatures on JD 214 for levels 1, 2, and 3, respectively, shows that the MK3 model does less well deeper in the canopy (levels 2 and 3). This is no doubt due to the combined effect of using the same value of stomatal resistance at each level, of using a constant value of windspeed, and of not accounting for canopy storage terms.

5. REFERENCES

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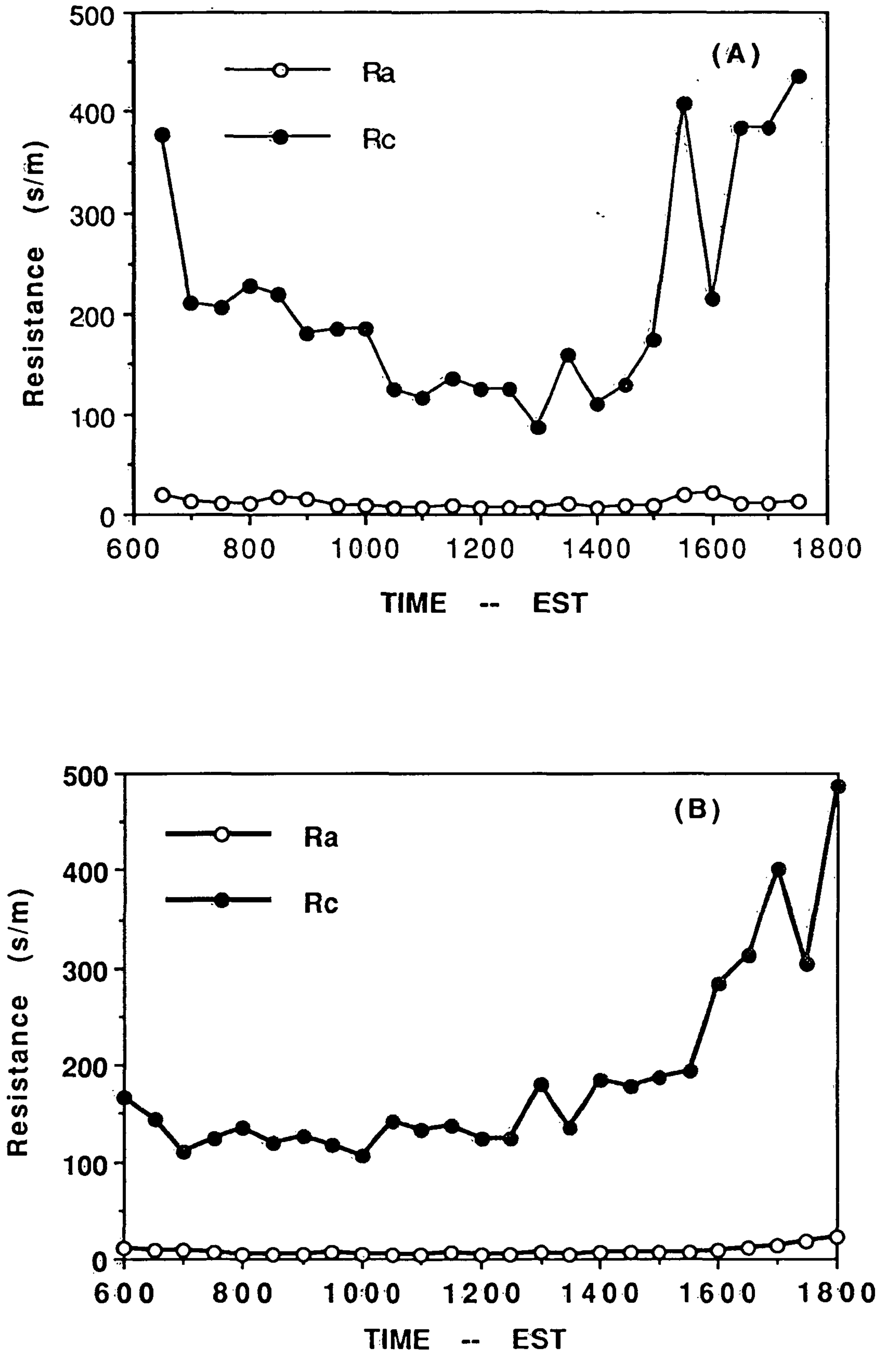

Fig. 2. Resistances for (A) 27 August 1989 and (B) 2 August 1990.

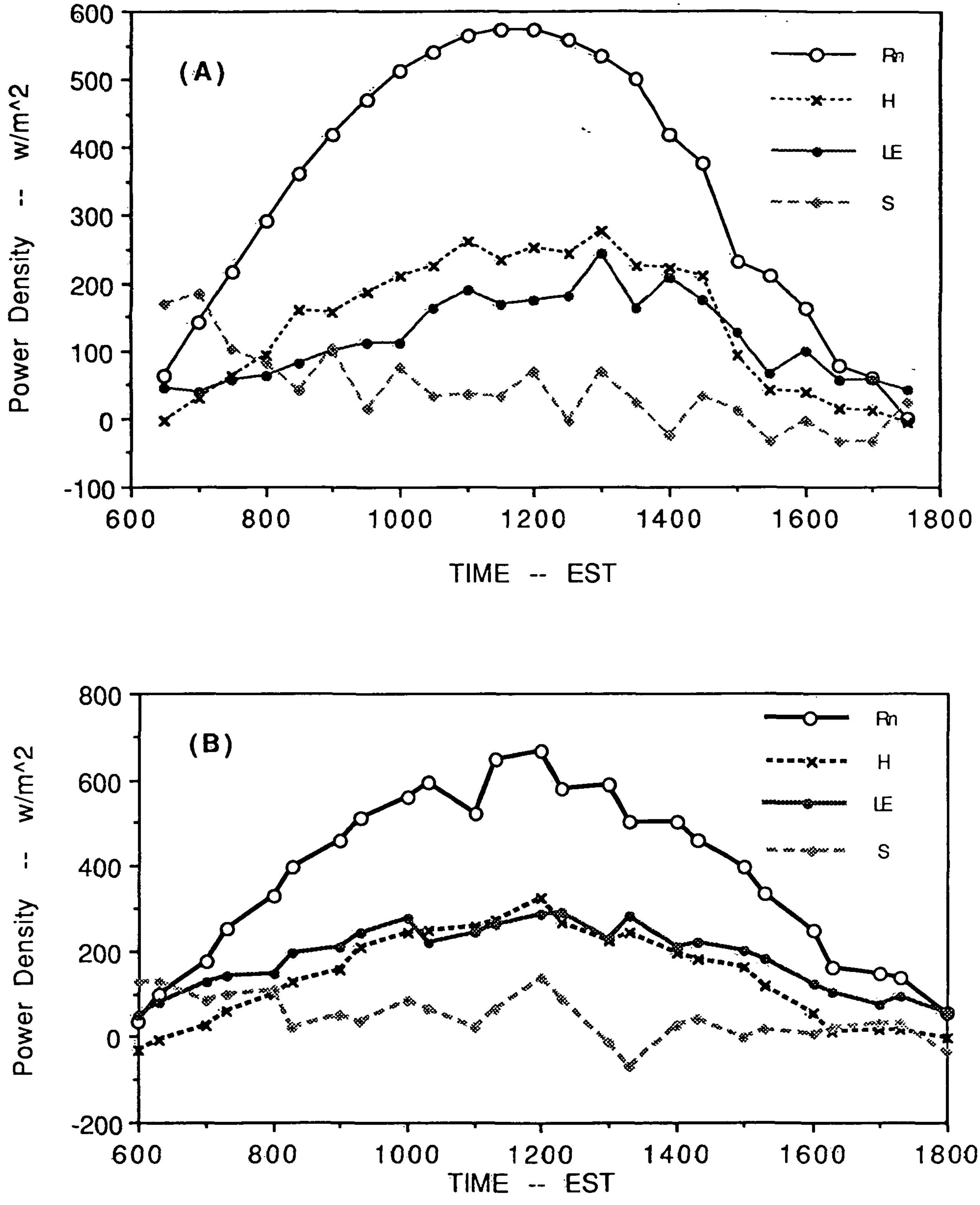

Fig. 1. (A) 27 Aug. 1989 and (B) 2 August 1990. Rn is net radiation, H is sensible heat flux density, LE is latent heat flux density, and S is soil and canopy storage.

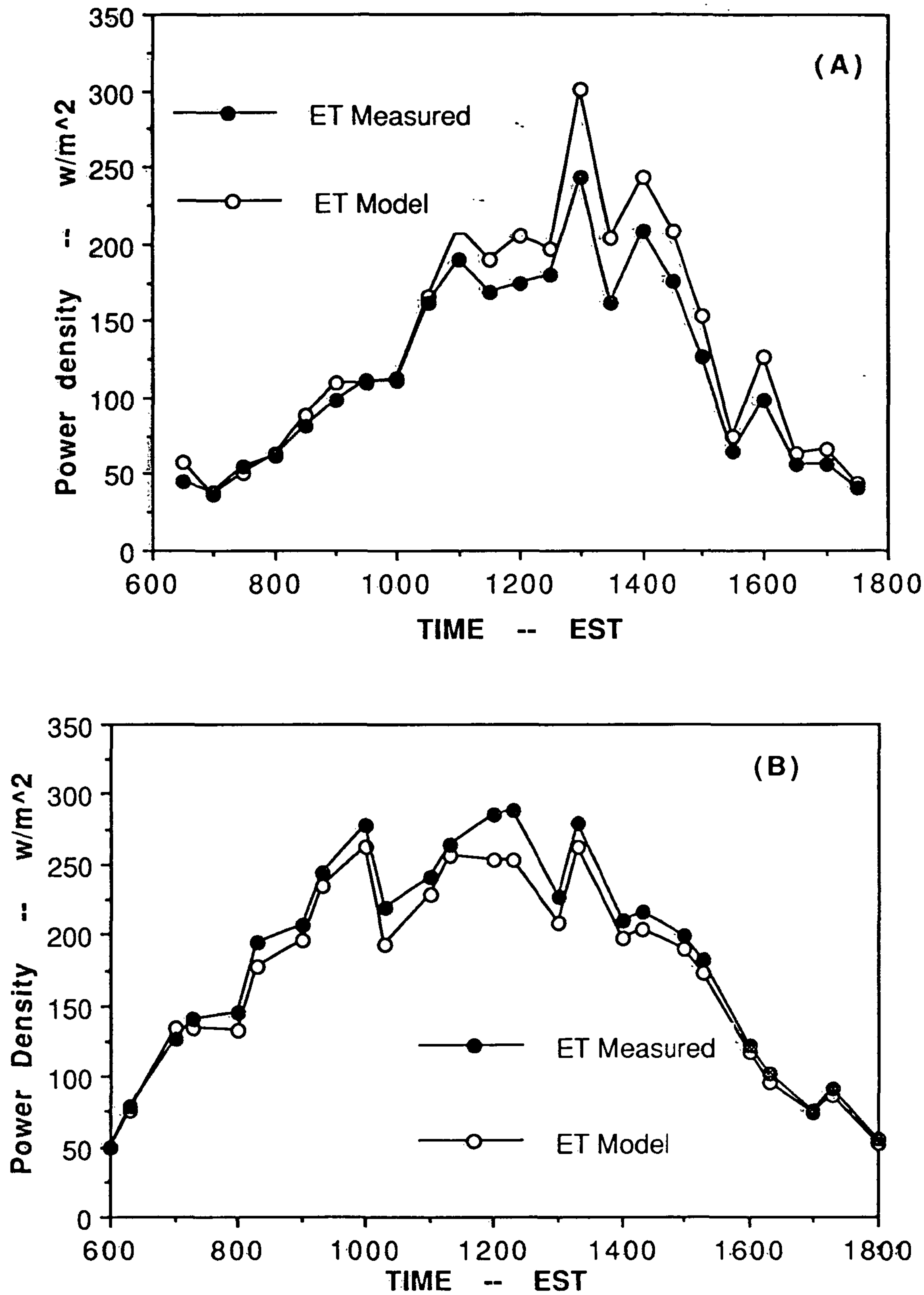

Fig. 3. Measured and modelled ET for (A) 27 August 1989 and (B) 2 August 1990.

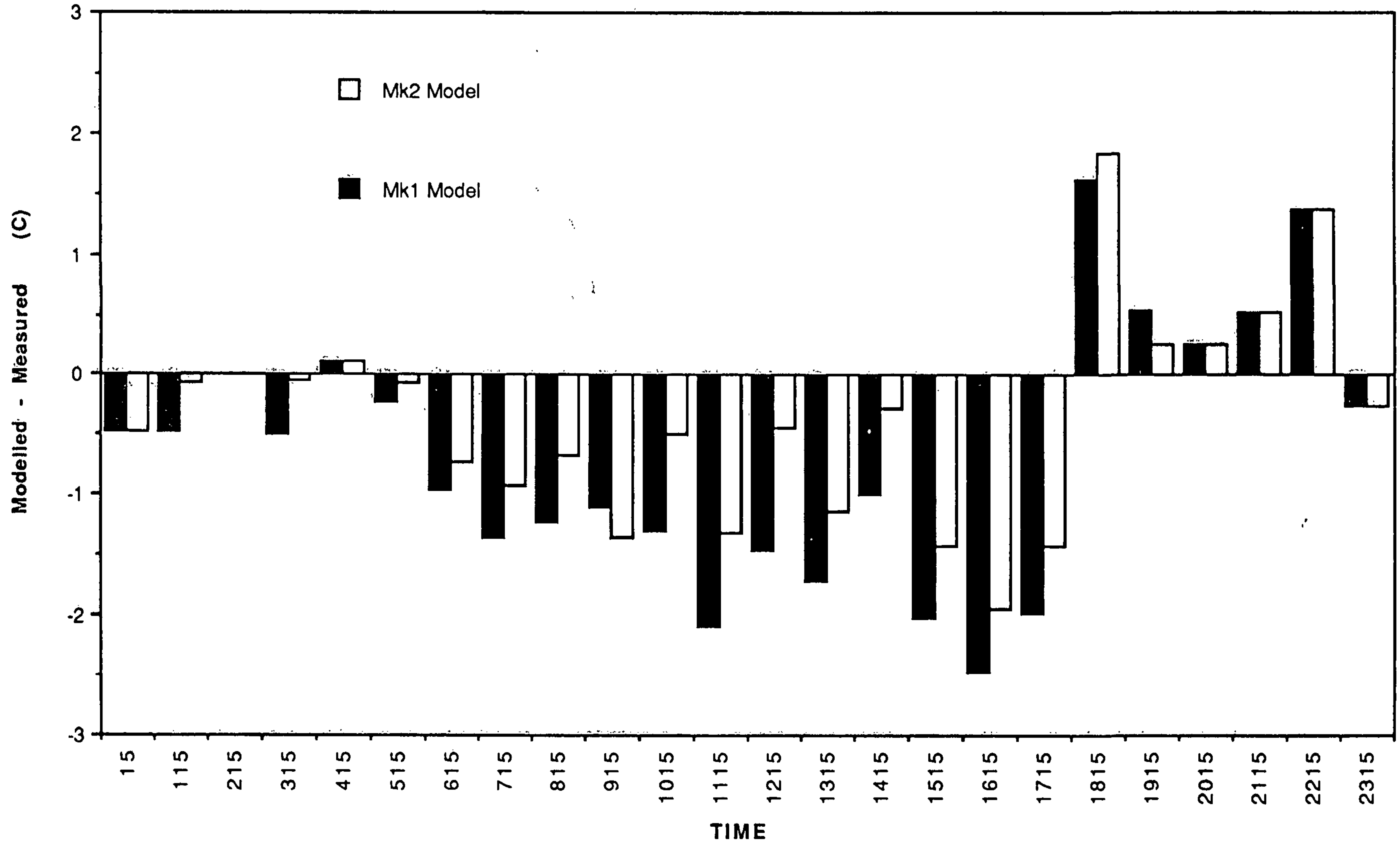

Fig. 4. MK1 and MK2 differences from measured values for 2 August 1990.

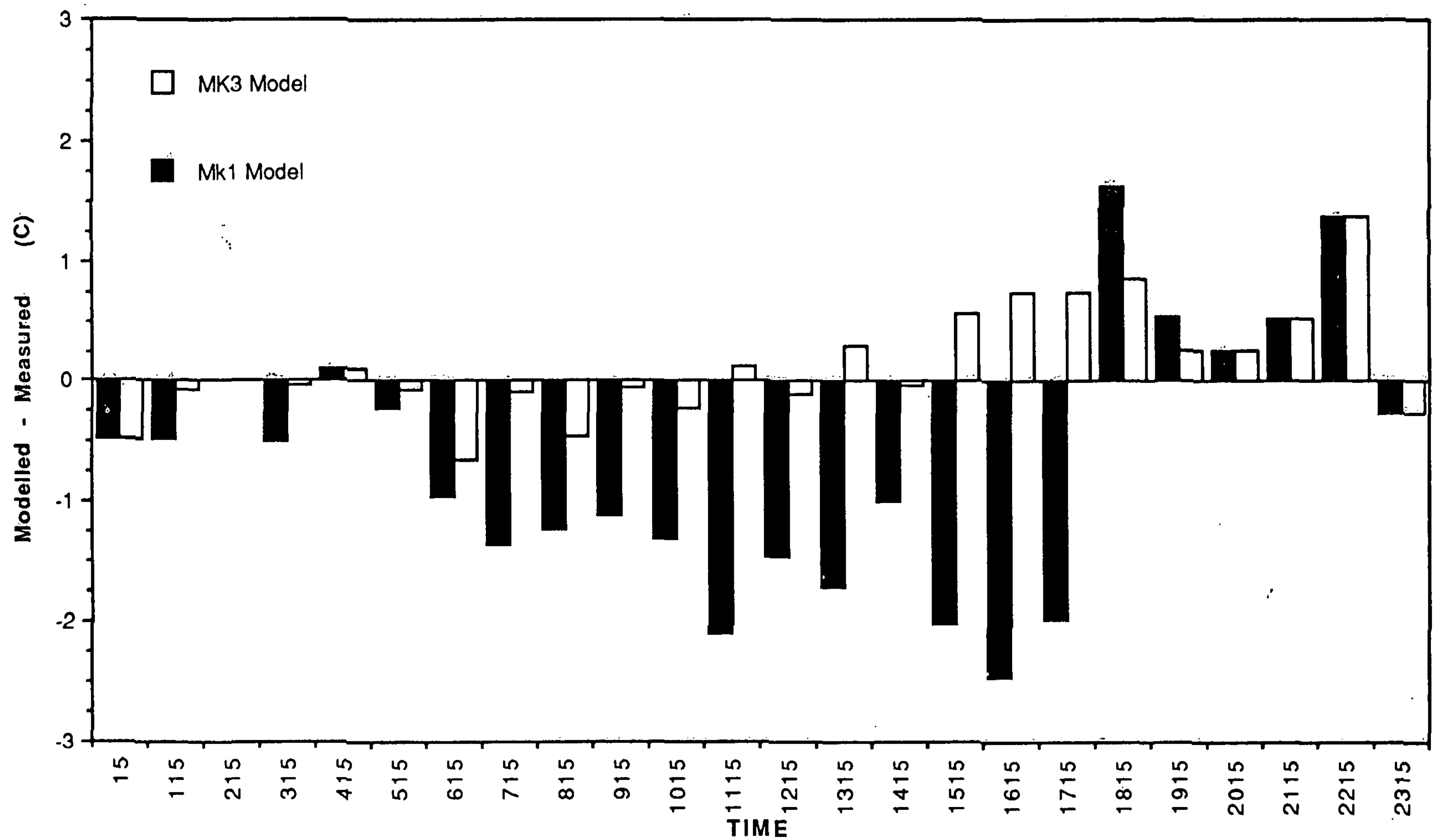

Fig. 5. MK1 and MK3 differences from measured values for 2 August 1990.

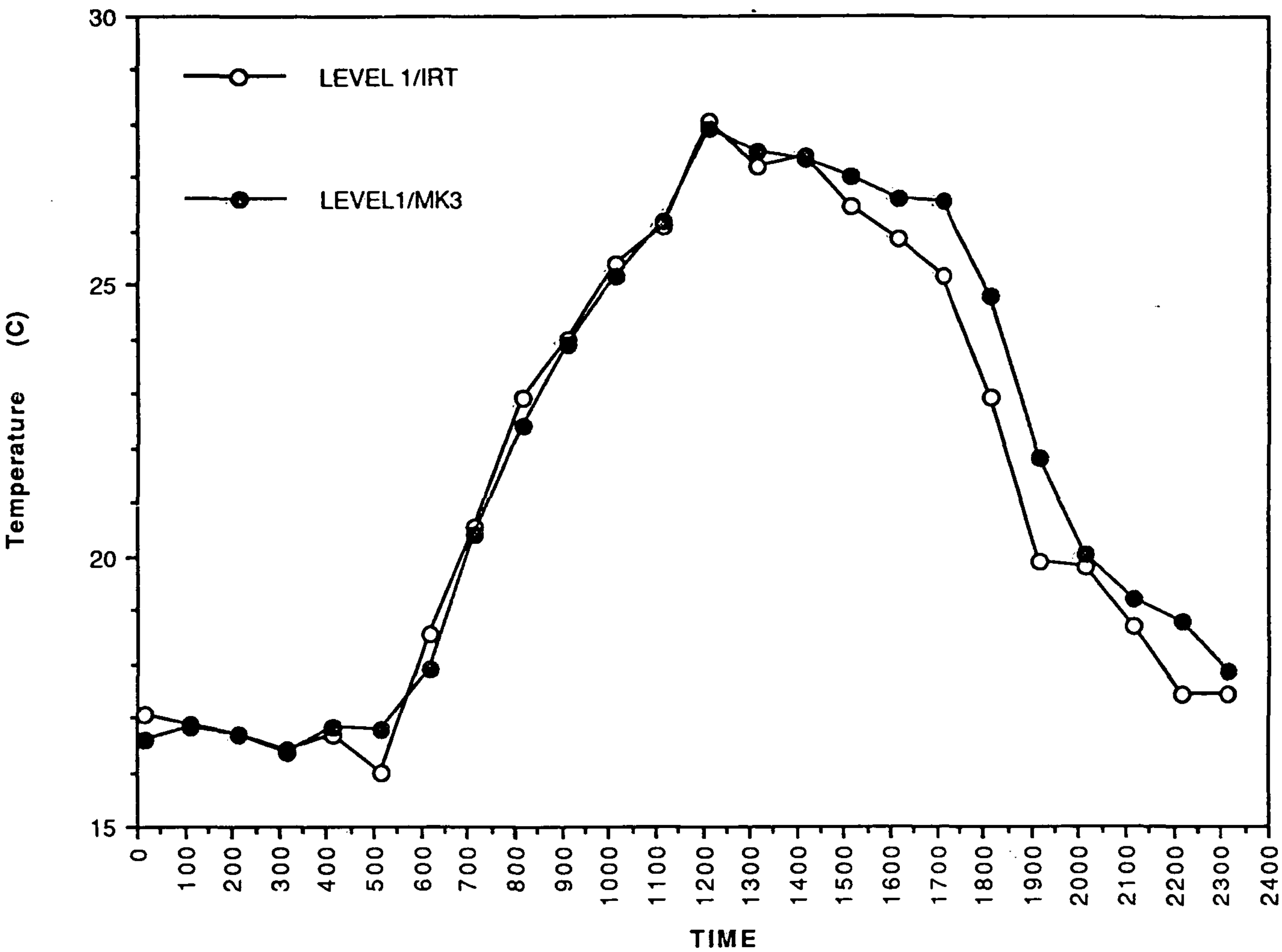

Fig. 6. Hourly level 1 MK3 temperatures vs. measured for JD 214.

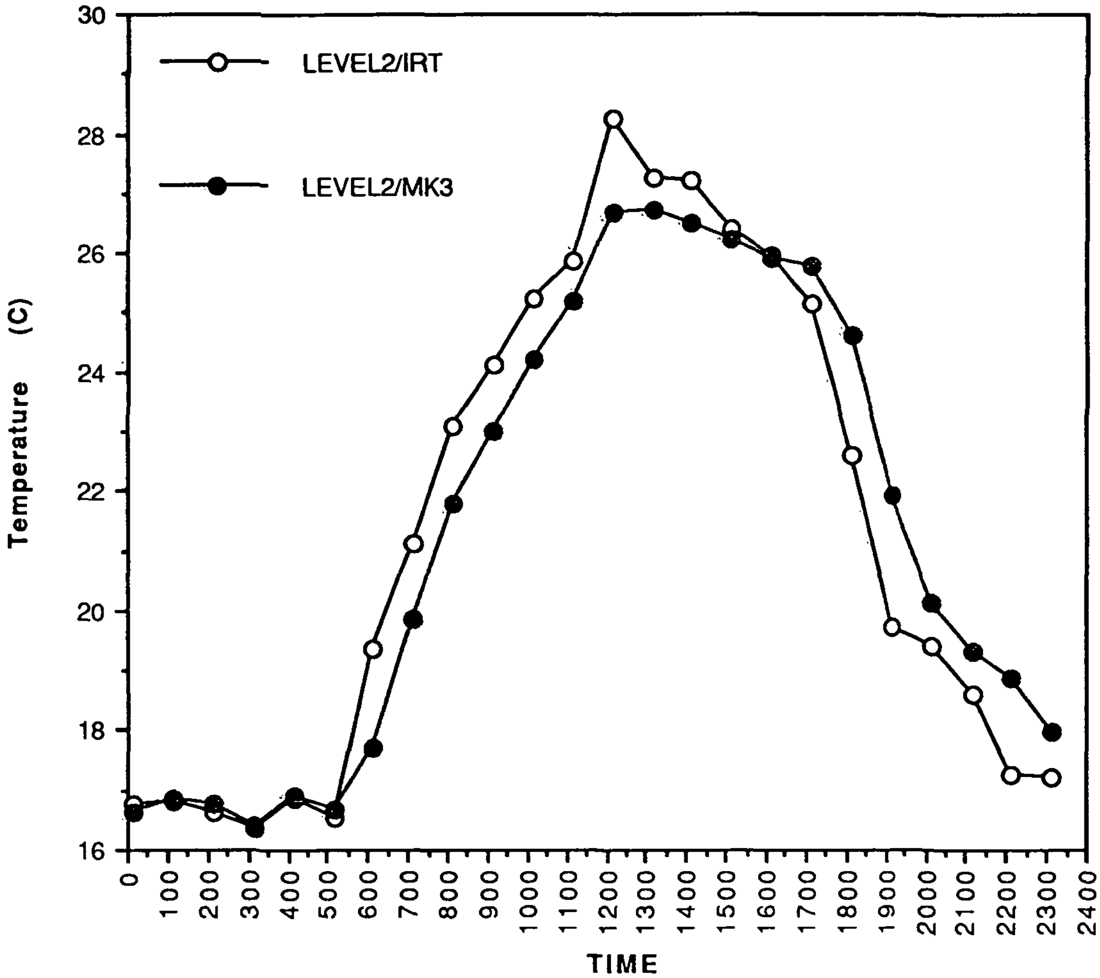

Fig. 7. Hourly level 2 MK3 temperatures vs. measured for JD 214.

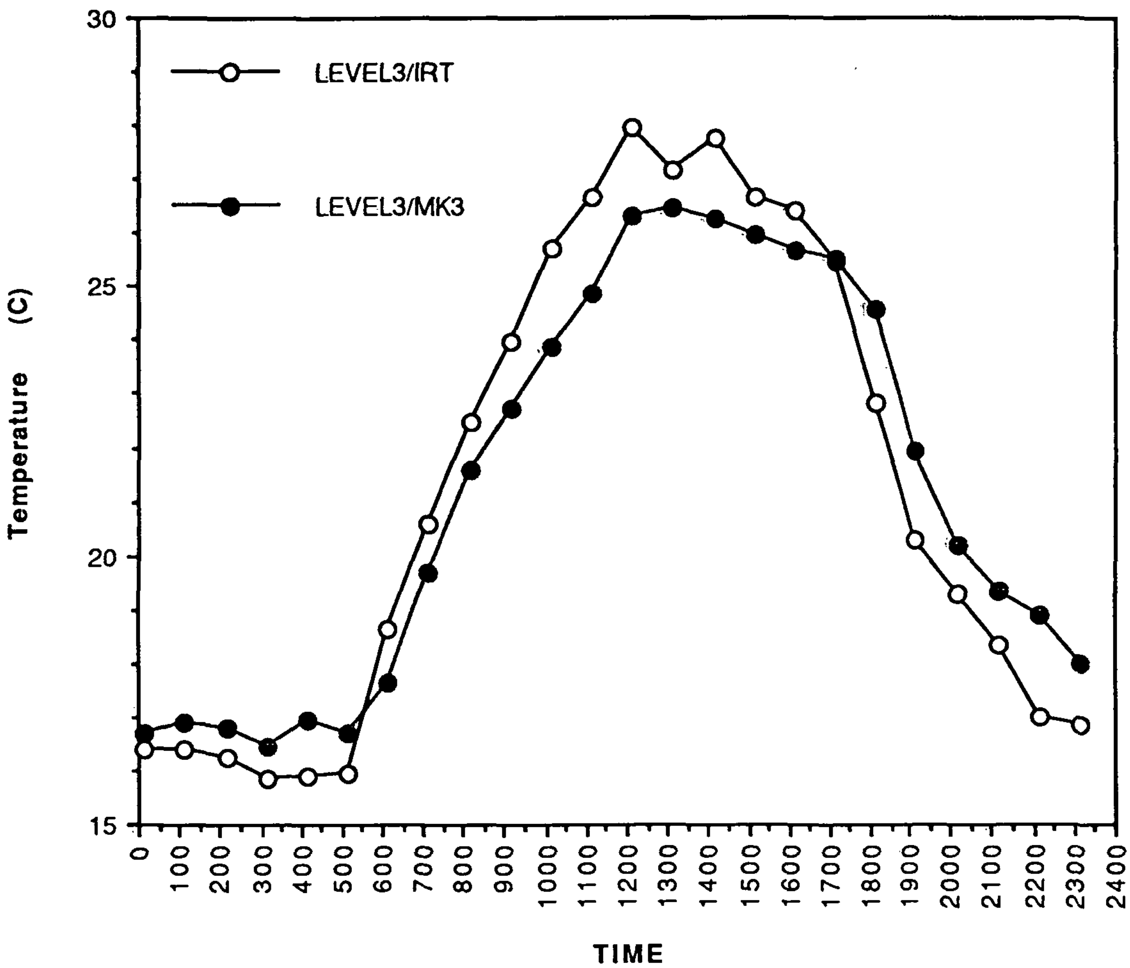

Fig. 8. Hourly level 3 MK3 temperatures vs. measured for JD 214.